



TRMM/LIS and GLM Lightning Optical Energies

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Overview

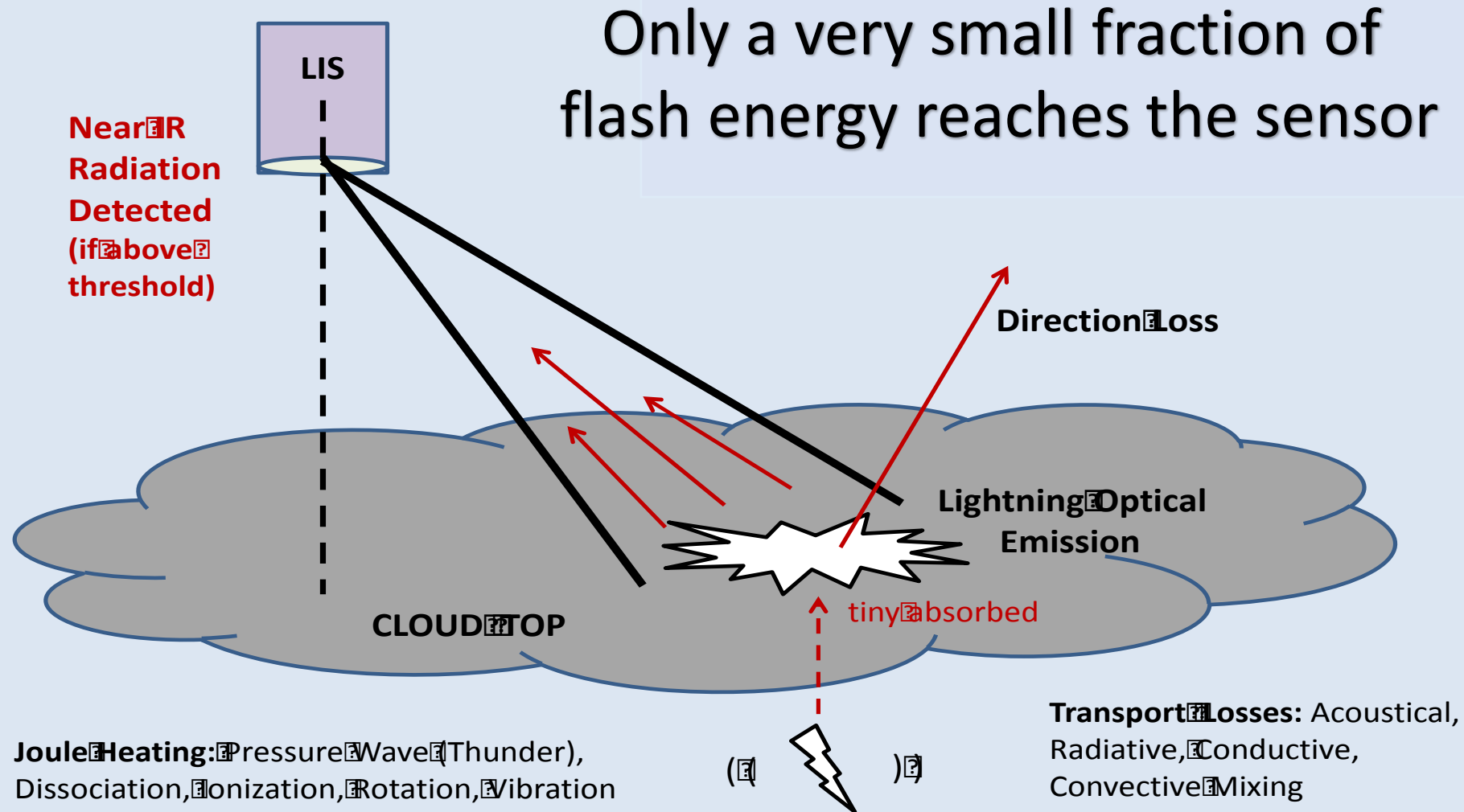
- General Comments
- Relationships Between Fundamental Quantities
- Analysis of OTD & TRMM/LIS Measurements
- Metrics
- Comparisons
- Trends

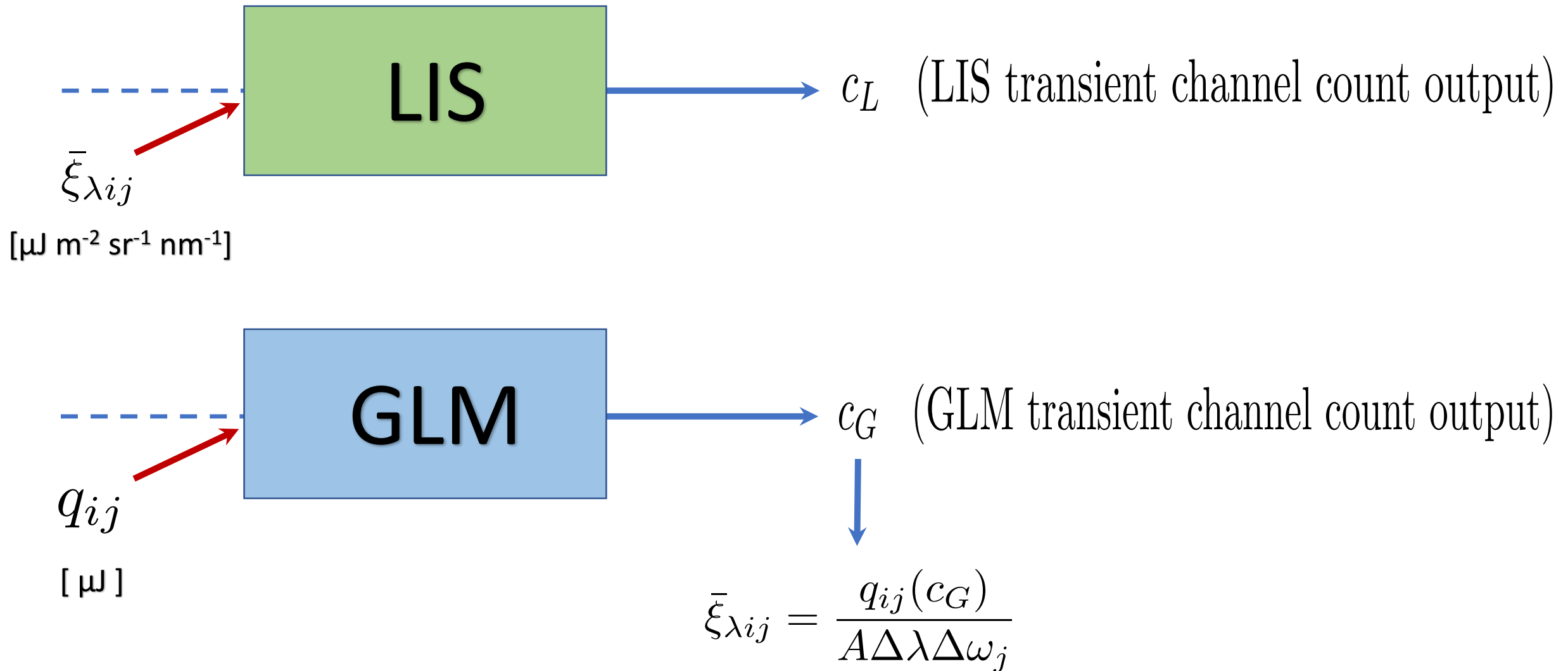
General Comments

Incident Energy is a Very Small Fraction of Flash Energy

- 
- **E : Flash Energy (GJ)** is huge and is dissipated by acoustical waves, **radiation**, thermal conduction, & convection (mixing)
 - **radiation**: radio, microwave, **IR**, visible, UV, X-Ray, gamma
 - **near IR Flash Optical Energy** emitted through 4π steradians
 - **Q : Incident Flash Optical Energy (~hundred or hundreds of fJ, depending on sensor)** = energy of the sliver ($< 4\pi$) of multiple-scattered near IR photons incident on sensor. **$Q/E \sim 10^{-22}$**
 - **Q^* : The portion of Q converted to digital counts** = Q minus losses (reflections, lens absorption, CCD quantum efficiency) and then converted to photoelectrons \rightarrow voltage \rightarrow digital counts.

Energy Flow





Relationships Between Fundamental Quantities

$$\left(\left\langle \xi_{\lambda}(\hat{\Omega}) \right\rangle, q_{ij}^*, \Phi_{\lambda} \right)$$



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$$\begin{aligned}\langle \xi_\lambda(\hat{\Omega}) \rangle &= \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \left[\int_{t_o}^{t_m} I_\lambda(\hat{\Omega}, t) dt \right] d\Omega = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \left[\sum_{i=1}^m \int_{t_{i-1}}^{t_i} I_\lambda(\hat{\Omega}, t) dt \right] d\Omega = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \left[\sum_{i=1}^m \xi_{\lambda i}(\hat{\Omega}) \right] d\Omega \\ &= \frac{1}{\Delta\Omega} \sum_{i=1}^m \left[\int_{\Delta\Omega} \xi_{\lambda i}(\hat{\Omega}) d\Omega \right] = \frac{1}{\Delta\Omega} \sum_{i=1}^m \left[\sum_{j=1}^n \int_{\Delta\omega_j} \xi_{\lambda i}(\hat{\Omega}) d\Omega \right] = \frac{1}{\Delta\Omega} \sum_{i=1}^m \sum_{j=1}^n \Delta\omega_j \bar{\xi}_{\lambda ij} \simeq \frac{\Delta\omega}{\Delta\Omega} \sum_{i=1}^m \sum_{j=1}^n \bar{\xi}_{\lambda ij}\end{aligned}$$

Hence:

$$\langle \xi_\lambda(\hat{\Omega}) \rangle \simeq \frac{1}{n} \sum_{i=1}^m \sum_{j=1}^n \bar{\xi}_{\lambda ij}$$

Solid Angle Averaged Spectral Energy Density
(in $\mu J \text{ m}^{-2} \text{ sr}^{-1} \mu m^{-1}$)

where:

$i = 1, \dots, m$ ($m = \#$ frames covered by the flash)

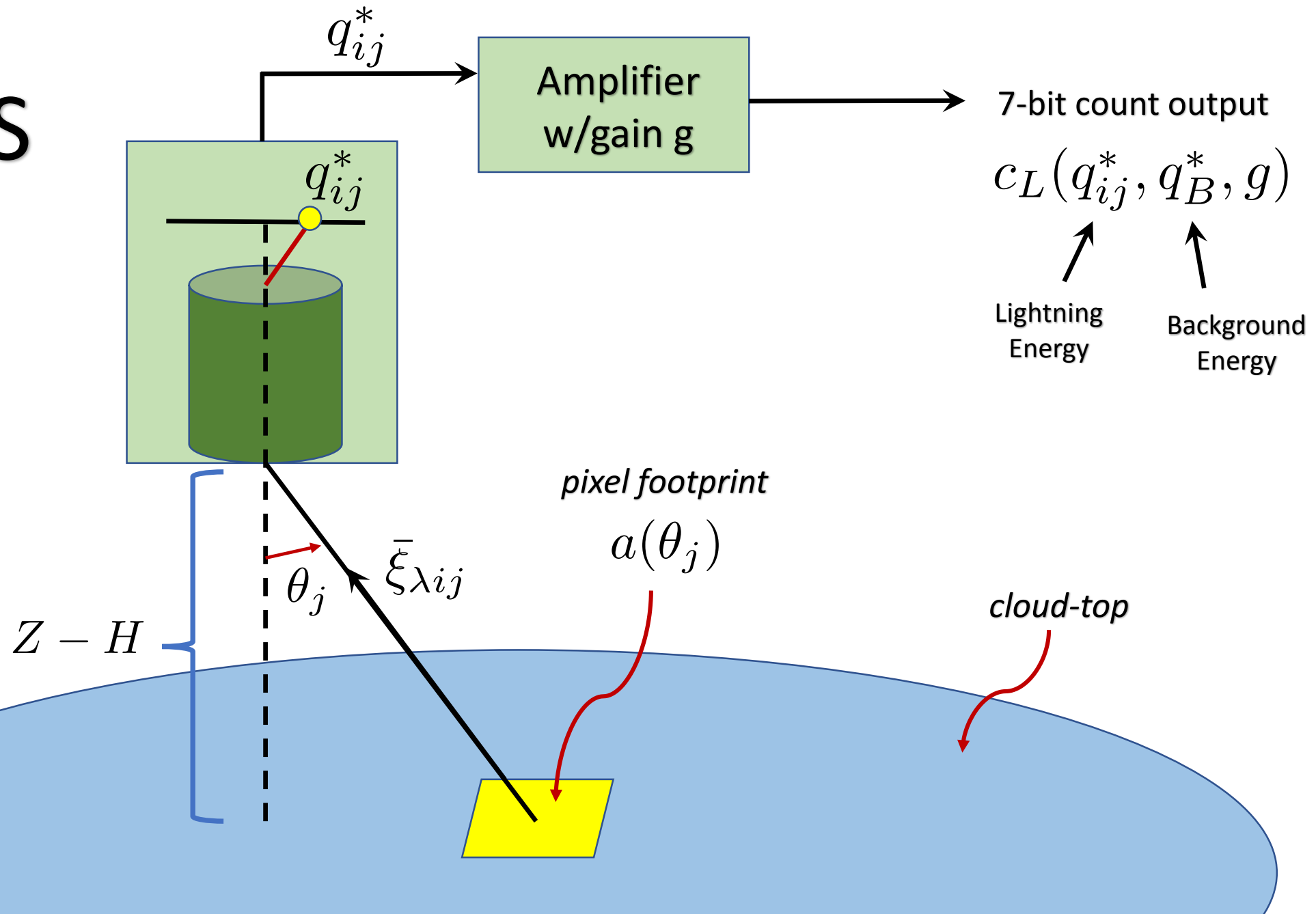
$j = 1, \dots, n$ ($n = \#$ pixels illuminated by the flash $\neq \#$ of EVENTS!, in general)

$\xi_{\lambda i}(\hat{\Omega}) \equiv \int_{t_{i-1}}^{t_i} I_\lambda(\hat{\Omega}, t) dt$ = spectral energy density function in i^{th} frame

$\bar{\xi}_{\lambda ij} \equiv \frac{1}{\Delta\omega_j} \int_{\Delta\omega_j} \xi_{\lambda i}(\hat{\Omega}) d\Omega$ = mean spectral energy density heading toward j^{th} pixel in i^{th} frame

$\Delta\Omega = \sum_{j=1}^n \Delta\omega_j = n\Delta\omega$ = flash solid angle; $\Delta\omega \equiv \frac{1}{n} \sum_{j=1}^n \Delta\omega_j$ = mean pixel solid angle in the flash

LIS



$$q_{ij}^* = \int_{t_{i-1}}^{t_i} \int_{\Delta\omega_j} \left[\varepsilon(\hat{\Omega}) \tau(\hat{\Omega}) A(\hat{\Omega}) b(\hat{\Omega}) \right] I_\lambda(\hat{\Omega}, t) d\Omega dt = \int_{t_{i-1}}^{t_i} \int_{\Delta\omega_j} K(\hat{\Omega}) I_\lambda(\hat{\Omega}, t) d\Omega dt$$

$$= \int_{\Delta\omega_j} K(\hat{\Omega}) \left[\int_{t_{i-1}}^{t_i} I_\lambda(\hat{\Omega}, t) dt \right] d\Omega = \int_{\Delta\omega_j} K(\hat{\Omega}) \xi_{\lambda i}(\hat{\Omega}) d\Omega \cong K(\hat{\Omega}_j) \int_{\Delta\omega_j} \xi_{\lambda i}(\hat{\Omega}) d\Omega$$

But,

$$\bar{\xi}_{\lambda ij} \equiv \frac{1}{\Delta\omega_j} \int_{\Delta\omega_j} \xi_{\lambda i}(\hat{\Omega}) d\Omega$$

Hence,

$$q_{ij}^* \cong K(\hat{\Omega}_j) \Delta\omega_j \bar{\xi}_{\lambda ij}$$

Energy Ingested by Pixel (in μJ)

where:

$$K(\hat{\Omega}_j) = K(\hat{\Omega}(\theta_j, \varphi_j)) = K(\theta_j, \varphi_j) \cong K(\theta_j)$$

$$\Delta\omega_j = \Delta\omega(\hat{\Omega}(\theta_j, \varphi_j)) = \Delta\omega(\theta_j, \varphi_j) \cong \Delta\omega(\theta_j)$$

$$\hat{\Omega}_j = \hat{\Omega}(\theta_j, \varphi_j)$$

$$\varepsilon(\hat{\Omega}) = \text{pixel quantum efficiency}$$

$$\tau(\hat{\Omega}) = \text{lens system transmission (i.e., there exists absorption \& reflection)}$$

$$A(\hat{\Omega}) = \text{entrance pupil area}$$

$$b(\hat{\Omega}) = \text{filter bandwidth}$$

} **Azimuthal Symmetry Assumed**

But, the DC count output for pixel energy q_{ij}^* [units of μJ] is:

$$C_{ij} = G_l q_{ij}^* + y_l$$

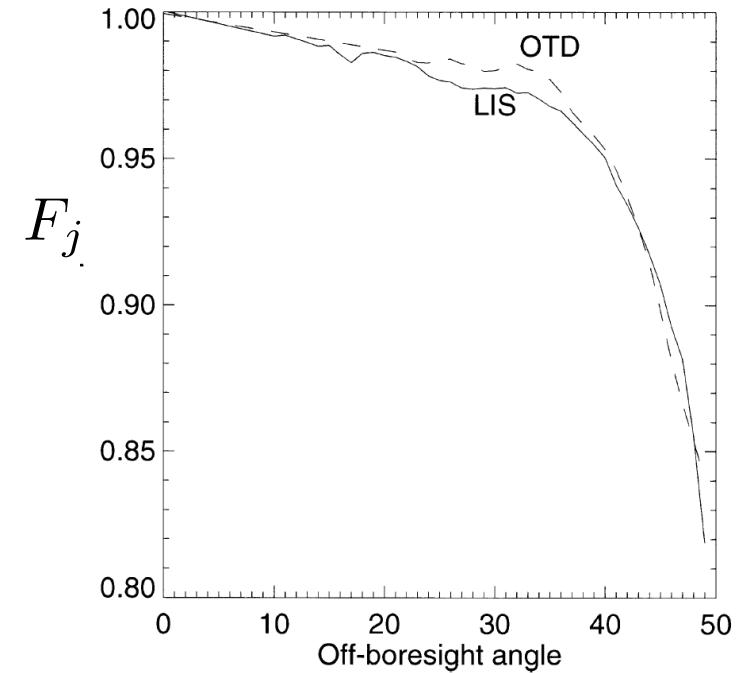
where:

G_l = DC gain of the l^{th} quadrant; $l = 1, 2, 3, 4$

y_l = DC offset of the l^{th} quadrant

So variation F_j in energy ingested by pixel relative to boresight $\theta_0 = 0$ is :

$$F_j = F(\theta_j) \equiv \frac{q_{ij}^*}{q_{i0}^*} = \frac{C_{ij} - y_l}{C_{i0} - y_l} \cong \frac{C_{ij}}{C_{i0}}$$

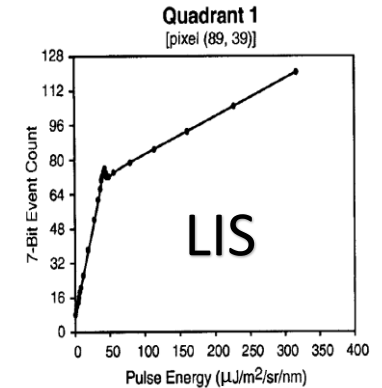
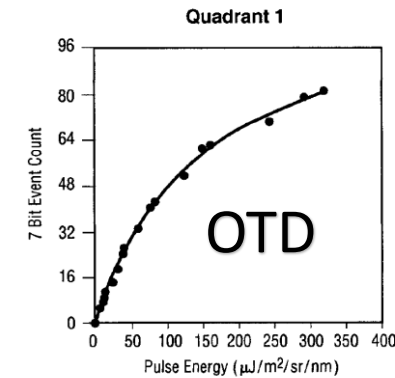


Boccippio, D. J., W. J. Koshak, R. J. Blakeslee, Performance assessment of the Optical Transient Detector and Lightning Imaging Sensor. Part I: predicted diurnal variability, J. Atmos. Oceanic Technol., 19, 1318-1332, 2002.

OTD/LIS Flash Radiance Data Product:

$$\Phi_{\lambda} \equiv \sum_{i=1}^m \sum_{j=1}^n \zeta_{\lambda ij}(c)$$

(in $\mu J m^{-2} sr^{-1} \mu m^{-1}$)



Koshak, W. J., M. F. Stewart, H. J. Christian, J. W. Bergstrom, J. M. Hall, and R. J. Solakiewicz, Laboratory Calibration of the Optical Transient Detector and the Lightning Imaging Sensor, J. Atmos. Oceanic Technol., 17, 905-915, 2000.

where c is the OTD or LIS 7 - bit count output.

By correcting the HDF data product $\zeta_{\lambda ij}(c_L)$, one can estimate the true incidence:

$$\bar{\xi}_{\lambda ij} \cong \frac{0.985 \zeta_{\lambda ij}(c_L)}{F_j}$$

So put all the pieces together:

$$\langle \xi_{\lambda}(\hat{\Omega}) \rangle \simeq \frac{1}{n} \sum_{i=1}^m \sum_{j=1}^n \bar{\xi}_{\lambda ij} \simeq \frac{1}{n} \sum_{i=1}^m \sum_{j=1}^n \frac{0.985 \zeta_{\lambda ij}(c_L)}{F_j}$$

$$\Phi_{\lambda} \equiv \sum_{i=1}^m \sum_{j=1}^n \zeta_{\lambda ij}(c)$$

But, a flash is fairly localized to one boresight region so that $F_j \simeq \bar{F}$:

$$\langle \xi_{\lambda}(\hat{\Omega}) \rangle \simeq \frac{0.985}{n\bar{F}} \sum_{i=1}^m \sum_{j=1}^n \zeta_{\lambda ij}(c_L) = \frac{0.985}{n\bar{F}} \Phi_{\lambda}$$

Hence:

$$\Phi_{\lambda} \simeq \frac{n\bar{F}}{0.985} \langle \xi_{\lambda}(\hat{\Omega}) \rangle$$

So data product generally overestimates true incidence by about a factor of n .
At max boresight the correction is $n(0.82)/0.985 = 0.832n$

$n \sim (\text{flash area})/(\text{pixel footprint})$

Analysis of OTD & TRMM/LIS Measurements

Summary

Heritage Flash Amplitude Baseline Computed by Koshak Using Raw Data Results from Various Investigators

Raw Data Source	Koshak OTD CONUS 1999-2000 Z = 3 weighting Resolution Model	Koshak OTD CONUS 1999-2000 data weighting Resolution Model	Buechler & Christian LIS GLOBAL 1998-Jul 2001 Pre-boost Resolution Model	Buechler & Christian LIS GLOBAL Sep 2001-2013 Post-boost Resolution Model	Buechler & Christian LIS GLOBAL 1998-Jul 2001 Pre-boost Res: data 22.6 km ²	Buechler & Christian LIS GLOBAL Sep 2001-2013 Post-boost Res: data 25.3 km ²	Beirle et al. LIS GLOBAL 1998-2012 both Pre- & Post- Res: BC data 24.7 km ²
Koshak Computation	79.8	72.8	55.7	57.9	67.9	59.9	60.3

- OTD: poor sensitivity, only CONUS stats done, Z estimate ... not best to use.
- More data in LIS Post-Boost than in Pre-boost ... so Post-Boost better sample size
- Buechler & Christian study has 1 more year of data than the Beirle et al. study, and more specific mean event footprints (since Beirle didn't separate out Pre-boost from Post-boost).
- So best estimate currently is 6th column above (bolded).

$$\left\langle \xi_{\lambda}(\hat{\Omega}) \right\rangle \sim 60 \frac{\mu J}{m^2 sr nm}$$

Metrics

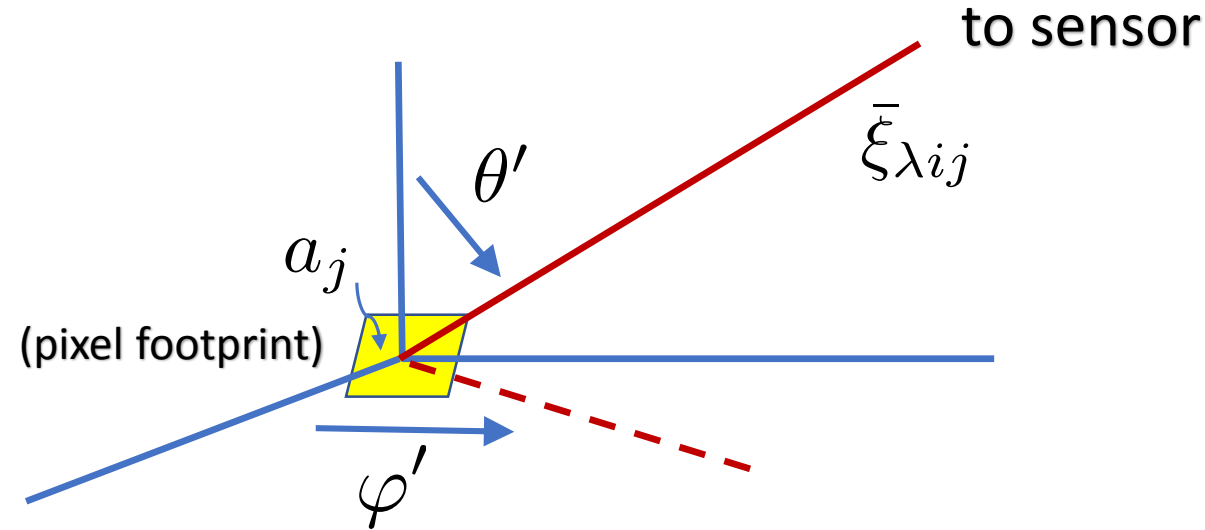
Three Candidates:

$$(1) \quad Q = \sum_{i=1}^m \sum_{j=1}^n q_{ij} = \sum_{i=1}^m \sum_{j=1}^n A_j \Delta \lambda_j \Delta \omega_j \bar{\xi}_{\lambda ij} \quad (\text{in } \mu J)$$

$$(2) \quad U_{\lambda} = \sum_{i=1}^m \sum_{j=1}^n u_{\lambda ij} = \sum_{i=1}^m \sum_{j=1}^n \Delta \omega_j \bar{\xi}_{\lambda ij} = \left\langle \xi_{\lambda}(\hat{\Omega}) \right\rangle \Delta \Omega \quad (\text{in } \mu J \text{ } m^{-2} n m^{-1})$$

$$(3) \quad \Gamma_{\lambda} = \sum_{i=1}^m \sum_{j=1}^n \gamma_{\lambda ij} = \sum_{i=1}^m \sum_{j=1}^n \pi \bar{\xi}_{\lambda ij} a_j \quad (\text{in } \mu J \text{ } n m^{-1})$$

isotropy assumed



$$J_{\lambda ij} = \int_{2\pi} \cos \theta' \bar{\xi}_{\lambda ij} d\Omega' = \bar{\xi}_{\lambda ij} \int_0^{2\pi} \int_0^{\pi/2} \cos \theta' \sin \theta' d\theta' d\varphi'$$

$$\Rightarrow J_{\lambda ij} = \pi \bar{\xi}_{\lambda ij} \quad (\mu J \text{ m}^{-2} \text{ nm}^{-1}) \quad \text{Upward flux density from pixel footprint for } i^{\text{th}} \text{ frame}$$

$$\Rightarrow \Gamma_{\lambda} = \sum_{i=1}^m \sum_{j=1}^n J_{\lambda ij} a_j = \sum_{i=1}^m \sum_{j=1}^n \pi \bar{\xi}_{\lambda ij} a_j$$

Γ_λ is the best Metric

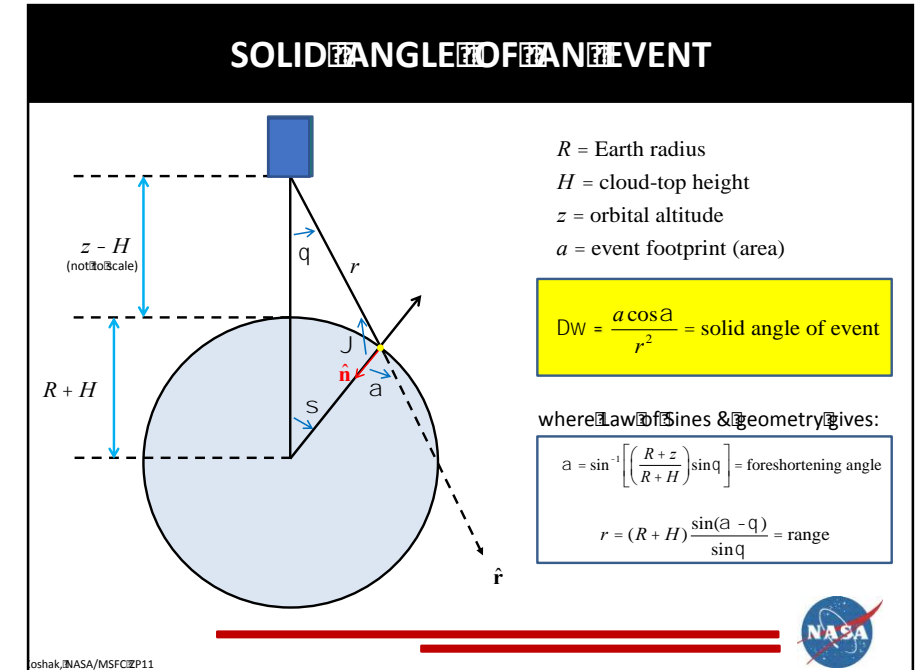
DEPENDENCES	Q	U_λ	Γ_λ
Depends on sensor orbit altitude z ? (i.e. on $\Delta\Omega$?)	YES	YES	NO
Depends on sensor A ?	YES	NO	NO
Depends on sensor $\Delta\lambda$?	YES	NO	NO
Accounts for flash cloud-top area S ?	YES*	YES*	YES

* Bigger $\Delta\Omega \Rightarrow$ bigger S , given z , but flash area is irritatingly modulated by boresight angle.

Comparisons

$$q_{ij} = \bar{\xi}_{\lambda ij} A \Delta \lambda \Delta \omega_j \sim \bar{\xi}_{\lambda} A \Delta \lambda \left(\frac{a_j \cos \alpha_j}{r_j^2} \right)$$

$$Q = \sum_{i=1}^m \sum_{j=1}^n q_{ij} = A \Delta \lambda \sum_{i=1}^m \sum_{j=1}^n \Delta \omega_j \bar{\xi}_{\lambda ij} = \left\langle \xi_{\lambda}(\hat{\Omega}) \right\rangle A \Delta \lambda \Delta \Omega$$



$$\begin{aligned}
 a_j &= a_j(\theta_j) & \{ \text{pixel footprint} \} \\
 r_j &= (R+z) \cos \theta_j - (R+H) \cos \alpha_j & \{ \text{range} \} \\
 \alpha_j & \text{ (see above)} & \{ \text{foreshortening angle} \}
 \end{aligned}$$

$$\bar{\xi}_{\lambda} \sim 14 \mu J \text{ m}^{-2} \text{ sr}^{-1} \text{ nm}^{-1}, \quad \left\langle \xi_{\lambda}(\hat{\Omega}) \right\rangle \sim 60 \mu J \text{ m}^{-2} \text{ sr}^{-1} \text{ nm}^{-1}$$

$$q = \bar{\xi}_\lambda A \Delta \lambda \Delta \omega$$

$$Q = \left\langle \xi_\lambda(\hat{\Omega}) \right\rangle A \Delta \lambda \Delta \Omega$$

Approximate Energy Ratios [L (LIS Postboost), G (GLM)] at halfway boresight angle:

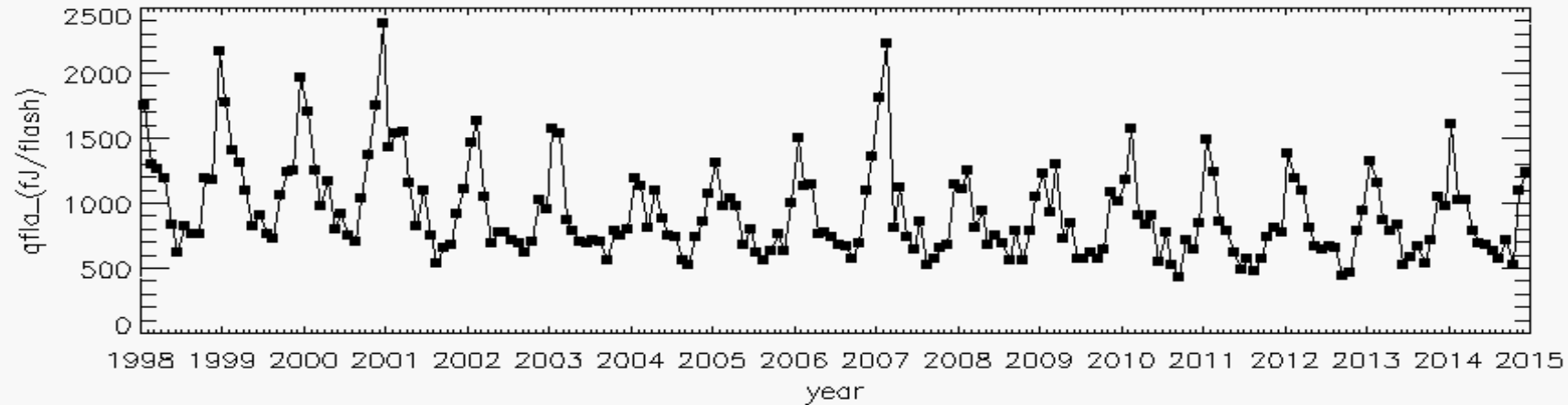
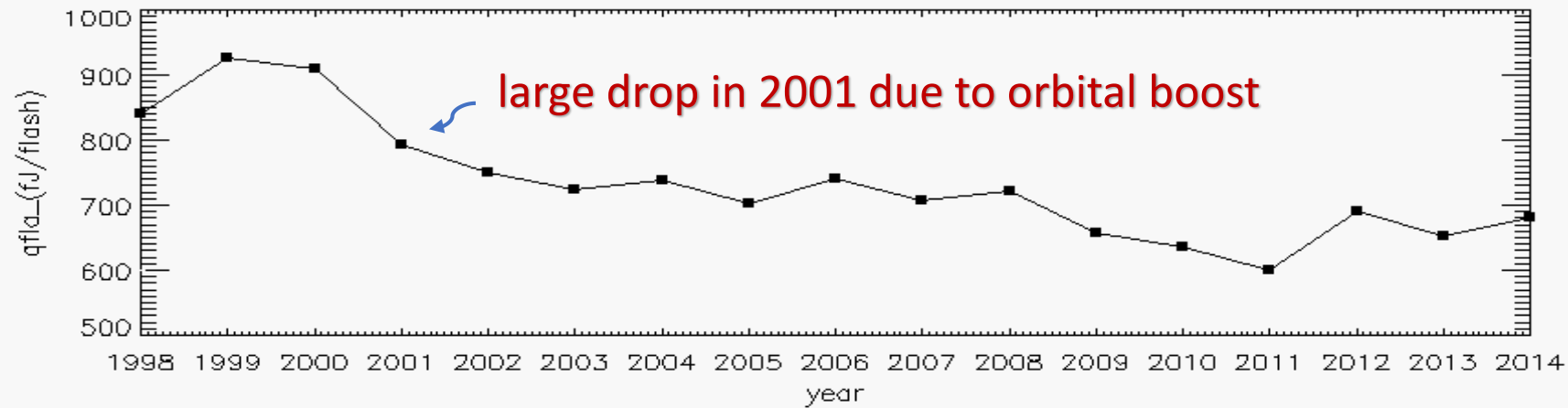
$$\frac{q_L}{q_G} \sim 1.7$$

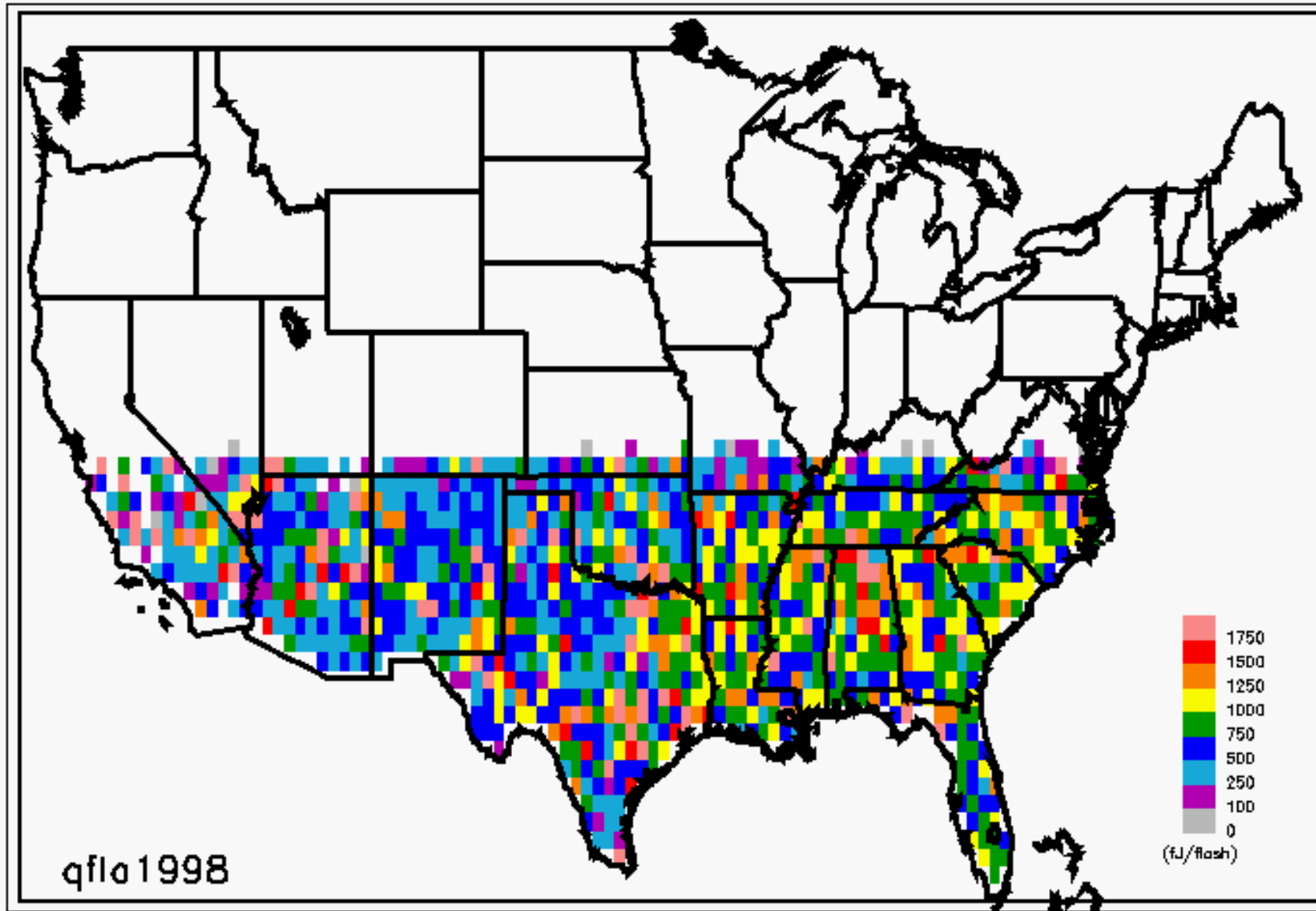
$$\frac{Q_L}{Q_G} \sim 6.7$$

... actual values depend on specific selection of solid angle values, so the 2 ratios can vary.

Trends

TRMM/LIS Incident Flash Optical Energy Q (fJ/flash)





**TRMM/LIS Incident
Flash Optical Energy
Q (fJ/flash)
Annual CONUS values**